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13. ABSTRACT *(Maximum 200 words)*

In the past year, our broad program of research has continued to explore efficient solutions fundamental problems of communication for wireless and wired networks, exploiting interrelated perspectives from communication theory, information theory, signal processing theory, control theory, and systems theory. As part of this work novel applications of fractal geometry, chaos, stochastic resonance, and other phenomena exhibited by nonlinear systems, are also being explored.

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Annual Progress Report for
ONR Grant No. N00014-96-1-0930

Fractal Point Process and Queueing Theory and Application to Communication Networks

for the period

June 1, 1997 through May 31, 1998

Principal Investigator: Prof. Gregory W. Wornell

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In the past year, our broad program of research has continued to explore efficient solutions fundamental problems of communication for wireless and wired networks, exploiting interrelated perspectives from communication theory, information theory, signal processing theory, control theory, and systems theory. As part of this work novel applications of fractal geometry, chaos, stochastic resonance, and other phenomena exhibited by nonlinear systems, are also being explored.

Practical, new, low-complexity coding and estimation algorithms for wireless sensor networks were developed that appear promising for a wide range of military applications. These involve the use of novel dynamic quantizer bias control techniques we have developed that were motivated by stochastic resonance phenomena observed in biological sensor systems prevalent in nature. These techniques are extremely economical in their use of power at the sensor.

We have also continued our development of ultra-low complexity error-correction coding strategies reliable transmission over known and unknown channels with feedback. These new methods adapt familiar, computationally efficient source coding algorithms for these channel coding applications. Recent work has focused on code-division multiple-access variants that efficiently accommodate multiuser scenarios, and on variants that allow the feedback rate to be optimized as a function of the application of interest. These techniques appear to be promising for a variety of wireless and related applications.

In other wireless communications research, we have continued to develop new techniques for exploiting multiple-element transmitter antenna arrays, which are particularly attractive for downlink communication from the base station in cellular systems. The techniques developed during this reporting period efficiently exploit channel state information to substantially enhance performance over existing approaches that ignore such information.

In related work, we have developed new "turbo-style" receiver structures for wireless communication systems subject to multipath fading effects. In these receivers, equalization, demodulation and decoding are performed via an efficient, low-complexity batch-interative algorithm, which provides a monotonically improving progression of symbol estimates that can be terminated at as desired to meet fidelity or computation constraints.

Finally, we have recently developed a new class of highly robust and efficient information embedding techniques for digital watermarking of media ranging from audio and video to a variety of types of imagery and graphics. These techniques involve the use of a natural "dither modulation" strategy for creating indexed familes of quantizers. From this framework, funda-

mental limits on reliable watermarking have also been developed. Emerging applications range from copyright protection to authentication. A US patent application has been filed for this promising invention.

The results for this reporting period are described in detail in the following theses, patent, and papers.

1. J. M. Ooi, "A Framework for Low-Complexity Communication over Channels with Feedback," Ph.D. thesis, Dept. Elec. Eng. Comp. Sci., MIT, Feb. 1998.

2. J. Nicolas Laneman, "Channel Estimation and Equalization for Spread-Response Precoding Systems in Fading Environments," S. M. thesis, Dept. Elec. Eng. Comp. Sci., MIT, June 1997.

3. B. Chen and G. W. Wornell, "System, Method, and Product for Information Embedding Using an Ensemble of Non-Intersecting Embedding Generators," US Patent filed May 1998.

4. S. Beheshti, S. H. Isabelle, and G. W. Wornell, "Joint Intersymbol and Multiple-Access Interference Suppression Algorithms for CDMA Systems" to appear in *European Transactions on Telecommunications,* Special Issue on Code-Division Multiple-Access Techniques for Wireless Communication Systems (invited paper).

5. H. C. Papadopoulos, G. W. Wornell, and A. V. Oppenheim, "Signal Encoding from Noisy Measurements using Quantizers with Dynamic Bias Control," submitted to *IEEE Trans. Inform. Theory.*

6. W. M. Lam and G. W. Wornell, "Multiscale Analysis and Control of Networks with Fractal Traffic," submitted to *IEEE Trans. Inform. Theory,* Special Issue on Multiscale Statistical Signal Analysis and its Applications.

7. A. Narula, M. J. Lopez, M. D. Trott, and G. W. Wornell, "Efficient Use of Side Information in Multiple-Antenna Data Transmission over Fading Channels," to appear in *IEEE J. Select. Areas Commun.,* Issue on Signal Processing for Wireless Communications.

8. J. M. Ooi, S. M. Verbout, J. T. Ludwig, and G. W. Wornell, "A Separation Theorem for Periodic Sharing Information Patterns in Decentralized Control," *IEEE Trans. Automat. Contr.*, vol. 42, no. 11, pp. 1546–1549, Nov. 1997.

9. B. Chen and G. W. Wornell, "Analog Error-Correcting Codes Based on Chaotic Dynamical Systems," to appear in *IEEE Trans. Commun.*

10. A. C. Singer, A. V. Oppenheim, and G. W. Wornell, "Detection and Estimation of Multiplexed Soliton Signals," to appear in *IEEE Trans. Signal Processing.*

11. J. M. Ooi and G. W. Wornell, "Fast Iterative Coding for Feedback Channels," in *Proc. IEEE Int. Sympo. Inform. Theory,* (Ulm, Germany), June 1997.

12. H. C. Papadopoulos and G. W. Wornell, "Distributed Estimation Techniques for Wireless Sensor Networks," in *Proc. Allerton Conf. Commun., Contr., Signal Processing,* (Illinois), Sept. 1997. (invited paper)

13. J. N. Laneman and G. W. Wornell, "Robust Equalization for Spread-Response Precoding Systems," in *Proc. Int. Conf. Acoust., Speech, Signal Processing,* (Seattle), May 1998.

14. H. C. Papadopoulos, G. W. Wornell and A. V. Oppenheim, "Low-Complexity Digital Encoding Strategies for Wireless Sensor Networks," in *Proc. Int. Conf. Acoust., Speech, Signal Processing,* (Seattle), May 1998.

15. J. M. Ooi and G. W. Wornell, "Further Results on Fast Iterative Coding for Feedback Channels: Multiple-Access and Partial-Feedback", to appear in *Int. Symp. Information Theory.*

16. M. J. Lopez and G. W. Wornell, "Transmitter Antenna Array Broadcasting with Side Information", to appear in *Int. Symp. Information Theory.*

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